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CONSTRUCTION OF THE DELAWARE MEMORIAL BRIDGE

By Homer R. Seely, M. ASCE

CONSTRUCTION AND STRUCTURAL DIVISION

Headquarters of the Society
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Technical Division	*Proceedings-Separate Number*
Air Transport	42, 43, 48, 52, 60, 93, 94, 95, 100, 103, 104, 108, 121, 130 (Discussion: D-XXVIII, D-7, D-16, D-18, D-23, D-43, D-75)
City Planning	58, 60, 62, 64, 93, 94, 99, 101, 104, 105, 115, 131, 138 (Discussion: D-16, D-23, D-43, D-60, D-62, D-65, D-86)
Construction	43, 50, 55, 71, 92, 94, 103, 108, 109, 113, 117, 121, 126, 130, 132, 133, 136, 137 (Discussion: D-3, D-8, D-17, D-23, D-36, D-40, D-71, D-75, D-92)
Engineering Mechanics	122, 124, 125, 126, 127, 128, 129, 134, 135, 136, 139, 141 (Discussion: D-24, D-33, D-34, D-49, D-54, D-61, D-96, D-100)
Highway	43, 44, 48, 58, 70, 100, 105, 108, 113, 120, 121, 130, 137, 138 (Discussion: D-XXVIII, D-23, D-60, D-75)
Hydraulics	50, 55, 56, 57, 70, 71, 78, 79, 80, 83, 86, 92, 96, 106, 107, 110, 111, 112, 113, 116, 120, 123, 130, 134, 135, 139, 141 (Discussion: D-70, D-71, D-76, D-78, D-79, D-86, D-92, D-96)
Irrigation and Drainage	97, 98, 99, 102, 106, 109, 110, 111, 112, 114, 117, 118, 120, 129, 130, 133, 134, 135, 138, 139, 140, 141 (Discussion: D-XXIII, D-3, D-7, D-11, D-17, D-19, D-25-K, D-29, D-30, D-38, D-40, D-44, D-47, D-57, D-70, D-71, D-76, D-78, D-80, D-86, D-87, D-92, D-96)
Power	48, 55, 56, 69, 71, 88, 96, 103, 106, 109, 110, 117, 118, 120, 129, 130, 133, 134, 135, 139, 141 (Discussion: D-XXIII, D-2, D-3, D-7, D-38, D-40, D-44, D-70, D-71, D-76, D-78, D-79, D-86, D-92, D-96)
Sanitary Engineering	55, 56, 87, 91, 96, 106, 111, 118, 130, 133, 134, 135, 139, 141 (Discussion: D-29, D-37, D-56, D-60, D-70, D-76, D-79, D-80, D-84, D-86, D-87, D-92, D-96)
Soil Mechanics and Foundations	43, 44, 48, 94, 102, 103, 106, 108, 109, 115, 130 (Discussion: D-4, D-XXVIII, D-7, D-43, D-44, D-56, D-75 D-86)
Structural	42, 49, 51, 53, 54, 59, 61, 66, 89, 100, 103, 109, 113, 116, 117, 119, 121, 122, 123, 124, 125, 126, 127, 128, 129, 132, 133, 136, 137 (Discussion: D-51, D-53, D-54, D-59, D-61, D-66, D-72, D-100)
Surveying and Mapping	50, 52, 55, 60, 63, 65, 68, 121, 138 (Discussion: D-60, D-65)
Waterways	41, 44, 45, 50, 56, 57, 70, 71, 96, 107, 112, 113, 115, 120, 123, 130, 135 (Discussion: D-8, D-9, D-19, D-27, D-28, D-56, D-70, D-71, D-78, D-79, D-80)

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

CONSTRUCTION OF THE DELAWARE MEMORIAL BRIDGE

By Homer R. Seely,[1] M. ASCE

Synopsis

All phases of the planning and construction of the Delaware Memorial Bridge, sixth longest suspension bridge in the world, spanning the Delaware River below Wilmington, Del., are described in this paper. The writer, project engineer on the bridge construction, describes the history and financing of the span and then details the various steps in erection.

Sinking of caissons for the river piers and anchorages is briefly described, followed by a comprehensive treatment of superstructure erection techniques. Erection of suspended footwalks for cable construction and the essential steps of cable spinning are given in detail. The paper also describes erection of the suspended steelwork and the placing of the concrete pavement.

Introduction

History.—For more than 50 years the ever-increasing demand for vehicular crossings on inland waterways of the United States generally has been met, even in some cases where the ultimate traffic does not justify their construction.

One notable exception to this general rule was the crossing of the Delaware River between Delaware and New Jersey south of Wilmington. At this location the need had been served since 1925 with diminishing success by the Pennsville-New Castle Ferry. Traffic lines miles in length waiting to cross the river on holiday weekends were common and on July 1, 1950, it was reported that a delay of 6 hr was suffered by some of the motorists, creating conditions requiring emergency aid from the police.

Although there had been proposals advanced by private interests to construct a crossing, nothing materialized until the State of Delaware, by legislation in 1939, directed the State Highway Department to investigate the legal,

Note.—Written comments are invited for publication; the last discussion should be submitted by January 1, 1953.

[1] Project Eng., Howard, Needles, Tammen & Bergendoff, Wilmington, Del.

engineering, and financial problems involved in constructing a crossing. These studies were completed and a report submitted in 1941. Although consideration was given to establishing some form of a bi-state organization with New Jersey, it was determined that this was not necessary since Delaware could undertake the construction alone. This was largely the result of the outcome of a boundary dispute starting back in colonial days, whereby the line between the present states of Delaware and New Jersey, within a 12-mile radius of New Castle, Del., was finally decreed by the Supreme Court to lie along the low-water mark on the New Jersey side of the river.

Legislation and Financing.—In 1945, immediately following World War II, the Delaware Legislature authorized the State Highway Department to construct, operate, and maintain a river crossing and to defray its cost by an issue of revenue bonds in an amount not to exceed $25,000,000.

An Act of Congress, passed in 1946, granted the state a franchise for a bridge meeting the requirements of the War and Navy departments. Enabling legislation also was passed by the State of New Jersey approving Delaware's proposal to construct a bridge and agreeing to accept title to such property and, if necessary, condemn such property within its boundaries as might be needed for the bridge approach.

The application for a War Department permit was made on August 27, 1946, and this was granted on March 15, 1947. The permit stipulated a horizontal clearance of 2,000 ft between fender lines measured normal to the channel and an underclearance of 175 ft above mean high water for a channel width of 1,500 ft, thus requiring the construction of a bridge having a center span of 2,150 ft, the sixth longest in the world. The site selected is about 3 miles south of Wilmington at which point the river narrows from Delaware Bay.

The legislation was amended to establish the Delaware Crossing Division of the Highway Department, and to authorize an increased bond issue of $40,000,000. The bonds were sold at a slight premium in June, 1948, carrying an interest rate of 4%. It had been planned to construct a six-lane bridge with highway connections extending from the du Pont Highway (Route 13) in Delaware to Route 44 in New Jersey. However, after taking bids for the tower and anchorage piers in January, 1948, it was evident that only a four-lane structure could be built and a contract for the construction of the piers on this basis was consummated in July, 1948. As bids for the remaining work were received, the continued rise in construction costs made it evident that there would not be sufficient funds to construct the highway approach on the Delaware side beyond New Castle Road, the first highway paralleling the river. The construction of the highway extending from this point westward to Route 13, including an interchange at either end, was then advanced by the state as a federal aid project. Costs continued to mount and in order to complete the bridge it finally became necessary to secure more funds. The State Legislature in its 1951 session authorized an additional bond issue of $3,900,000, part of which, however, is to be used to reimburse the state for the highway extension. Legislation was also passed at this session providing for a further bond issue to cover the cost of acquiring the ferry, which is an obligation of the Trust Inden-

ture. This extension in the amount of $2,500,000 was passed at a recent special session of the Legislature.

At the time of the initial studies in 1941, it was estimated that about 4,606,000 vehicles would cross the bridge in 1952, assuming that it would be open for traffic in 1944. In 1948 when the bonds were sold, this estimate was scaled downward to 3,817,000, reflecting the recession resulting from World War II. However, the rapidly mounting ferry traffic prior to the bridge opening on August 16, 1951, clearly justified rescaling the 1952 estimate to 5,130,000 vehicles, increasing to 7,677,000 by 1960. During the first six months of operation, the actual traffic totaled over 2,590,000 vehicles, with an average toll of approximately 83 cents. At this rate, amortization of the entire cost of the bridge before 1970 is assured.

Main Piers

Horizontal and Vertical Control.—Immediately after the contract for the main piers had been signed, steps were taken to establish the triangulation system required to locate the piers. The bridge center line had been arbitrarily located for the earlier studies and a preliminary triangulation system set up for locating the borings, making use to a large degree of the existing monuments of the Corps of Engineers, United States Department of the Army. The principal base line of the final system was laid out along a tangent section of a branch freight line of the Pennsylvania Railroad on the Delaware side, which line essentially parallels the river at this point. The base line was 6,547,222 ft in length. A check line 5,401,634 ft in length was laid out on the New Jersey side running through a high tension transformer station of the Deepwater Power Plant. The measurement of this line accordingly was somewhat precarious. The base line measurements were made by setting braced stakes at 100-ft stations with set scribe marks on copper plates fastened to the top of the stakes. Six sets of measurements were made of each line, rotating the personnel in the various positions to obtain an independent check. The average of four sets was used in each case, resulting in maximum variations of 0.017 ft and 0.045 ft, respectively.

Timber towers approximately 30 ft in height were required at each of the four primary stations in order to obtain clear lines of sight. Double towers were constructed, an inner tower for supporting the instrument surrounded by an independent tower and platform for the observers. The instrument was used with a trivet resting on a heavy bent steel plate securely bolted to the tower legs. It was centered by transit plumbing from the monument below. Observations were started with a 20-sec transit, but progress was slow because of the poor atmospheric conditions that existed much of the time. Accordingly, a theodolite, reading to 0.1 sec was acquired, materially speeding the remaining observations as well as those required during the sinking of the caissons. Two stations of the United States Engineers' network were tied into the system to simplify the proper location of the piers in relation to the center line of channel. The system also included two secondary stations to facilitate the pier location and to serve as controls during construction.

The United States Engineers' datum was used for vertical control, being established by a bench mark on the wall of the Deepwater Power Plant. Initially, water levels were used for the river and Delaware land piers but before final grades were set on any of these piers, sufficient work had been completed in the river so that it was possible to establish differential levels across the river.

Land Piers.—The construction of the piers has already been described at some length.[2,3] However, a brief description of the work will be included in this paper.

The approach piers are all founded on wood piles, driven to "practical refusal" (deemed to be to a bearing capacity of 35 tons). The footings of the New Jersey land piers were constructed in open excavations in which the ground-water level was lowered with well points. Jets were used in driving the piles to aid penetration through a firm layer of material overlaying the stratum in which refusal was obtained. The concrete was mixed at the site, with ingredients being delivered by rail.

On the Delaware side, the footings of the land piers were constructed in sheeted excavations extending through the land fill that had been previously placed over the marsh mud extending some 2,000 ft inland from the shoreline.

The sheeting consisted of timber panels inserted between the flanges of steel H-beams driven at predetermined locations around the pier footings, and braced at ground level with timber wales. In some cases, cross-struts were required to reinforce the wales and in a few cases additional bracing was installed at the bottom of the excavation. The most noteworthy feature of this operation was the general absence of water seepage through the marsh mud, which meant that very little pumping of the excavations was necessary. The shafts of piers W6 to W24, inclusive, were constructed with only three form units, two of which were progressively shortened at the bottom for piers W13 to W24, inclusive, and the lower pour of piers W6 to W12, inclusive. This necessitated pours up to nearly 30 ft in height. The concrete was mixed in a central mixing plant and trucked to the site.

River Piers.—The river approach piers were constructed by the conventional cofferdam method. Underwater steam hammers were used to drive the piles so as to reduce the length of cutoffs, for which no payment allowance was made. In order to obtain adequate penetration, the piles were fitted with steel shoes. Steel spud beams were used as leads for positioning and driving both vertical and batter piles. Upon completion of pile driving, the cofferdams were sealed with 5 ft of tremie concrete deposited on a 2-ft layer of sand placed upon the mud bottom. The balance of the pier construction was carried on in the open air. The pier bases were faced with granite above El.-5.0 ft.

The two tower piers and the west anchorage pier were constructed with open dredged caissons founded on layers of compact clay. The tower caissons were about 69 ft × 116 ft in size with four rows of seven dredge wells, each 15 ft in diameter. The east caisson was founded at El. −115.6 ft and the west caisson at El. −86.9 ft. The material under the sloping surfaces of the caisson

[2] "Mammoth Tremie Seal Poured in 7½-Day Continuous Operation," by Carl H. Cotter, *Civil Engineering*, November, 1950.

[3] "Forty-Million-Dollar Suspension Bridge to Link Delaware and New Jersey," by Homer R. Seely, *ibid.*, November, 1949.

walls and between the wells was loosened with water jets and removed with air lifts. The tower caissons were tremie sealed in a single operation to a plane 15 ft above the cutting edges. The two inside rows of wells were capped at El. +5 within the pier bases, which were faced with granite from El. −5 to the top of the base at El. +20. Buttresses between the outside wells extend from El. −6 down to El. −30, at which plane these wells were capped.

Anchorage Piers.—The caisson for the west anchorage pier was about 95 ft wide and 221 ft long and contained five rows of twelve dredge wells also 15 ft in diameter. This caisson was founded at El. −92.7 ft and sealed in three sections, the three westerly transverse rows of wells being cleaned and sealed first, followed in turn by the three easterly rows and then the six center rows. Care had to be taken not to dislodge the material under the cross-walls separating these areas until after the end sections had been sealed to prevent the tremie concrete from flowing prematurely into the center section. The easterly row of wells were capped at El. −20 to form a setback at this level, the remaining wells being capped at El. +5. A cofferdam extension to the caisson was used to construct an overhang at the west end. Granite facing was installed from El. −5 to the top of the pier at El. +15.

The cutting edges of the caissons were assembled at the Camden plant of the New York Shipbuilding Company. Welded construction was used throughout. Sheet pile sand islands were used to hold the caissons in position upstream and downstream and steel pile dolphins, in the other directions. Daily checks were made on the position and plumbness of the caissons during all stages of sinking and each was founded well within the tolerances set up in the specifications that permitted a maximum horizontal variation of 9 in. for the tower piers and 18 in. for the anchorage piers and a maximum variance from plumb of 9 in. per 100 ft of height.

Because of the short supply of plate steel, the east anchorage pier was constructed within a cofferdam about 99 ft × 225 ft in plan dimensions. After pre-dredging the river bed to El. −40, four units of welded steel bracing, weighing approximately 140 tons each, were successively lowered into their correct locations and supported on steel spud piles driven to below founding depth. The sheet piling was driven to refusal also well below the founding depth. The material within the cofferdam was dredged to a stratum of compact sand that existed at an average elevation of −68.5 ft and cleaned with an air lift. The cofferdam was sealed with 32 ft of concrete. This was placed in a continuous operation lasting about 7½ days, and required the mixing and placing of about 27,000 cu yd of concrete. The concrete was deposited in four passes of 8 ft each starting and ending at the east end. Air lifts were used toward the end of each layer to remove the accumulation of soft material that was pushed ahead of the tremie concrete. The cofferdam was pumped out at the end of 7 days and the balance of the pier constructed in the open air. Cellular construction was used, as was the case for the west anchorage.

No special steps were taken for controlling the temperature of the tremie concrete during the period of curing, other than reducing the cement content from 6½ to 5 bags per cu yd. As soon as possible after dewatering the cofferdam, five core holes 24 ft deep were drilled in the concrete and water temperatures

in these holes determined at three depths varying from about 2 ft to 22 ft. The difference in temperature at these depths generally was about 10° F. On September 14, 1949, 23 days after completing the seal, the maximum temperature observed was 142°. The rate of cooling at this stage was about 1° per day, decreasing to about 0.35° per day on November 10, 1949, on which date the observations had to be discontinued.

Concrete Handling.—The concrete for all the river piers was mixed in two floating mixer plants; one containing two mixers with 1-yd capacity, was generally used on the approach piers, and the other containing two mixers with 2-yd capacity, for the large piers. Both plants, however, placed the tremie seal of the east anchorage pier. Wherever possible, the concrete was deposited directly in the forms through chutes and elephant trunks. Bottom-dump buckets were used for the balance of the placement. Cement was shipped in bulk and transferred to barges at the Pigeon Point Terminal of the Reading Railroad, about one-half mile north of the bridge site. The aggregates were delivered by barge from their source approximately 30 miles up the river. During the placing of the east anchorage seal, five barge loads of aggregate were held in reserve to guard against delivery failures that, however, did not materialize.

Anchorages

The construction of the anchorage blocks followed immediately the completion of the foundation piers. This work included the erection and embedment of 900 tons of structural steel forming the anchors for the main cables. The outstanding feature of this construction was the heights to which the concrete was placed with the floating derricks; the buttresses supporting the cable saddles reached to El.+158 ft. About 23,200 cu yd of concrete were required for each anchorage block. Allowances of approximately 10 in. were made in the heights of the anchorage blocks to compensate for settlement. Since sealing the piers periodical surveys disclose that the settlement of the east anchorage has been about 3 in. and the west anchorage about 3.5 in.

Approach Superstructure

General.—Erection of the bridge superstructure began on February 15, 1950, at the west abutment, and on March 14 at the east abutment. The steel for the west approach was delivered over a specially constructed railroad siding built along the right of way to the river edge. On the New Jersey side, use was made of the relocated track leading to the Deepwater Power Plant, from which a siding had been extended to the river by the pier contractor. The steelwork for placement over the water was shipped to the Wilmington Marine Terminal, at which point it was reloaded on steel barges for delivery to the bridge site.

The trusses, girders, floorbeams, and stringers were fabricated at Ambridge, Pa., and the balance of the steel consisting principally of the brackets, sidewalk and fascia units, and center median curbs, at Trenton, N. J. About 14,900 tons of steel were required for both approaches.

Approach Span Erection.—The continuous girder spans were erected by crawler cranes working on the ground. The truss spans were erected on falsework bents by the cantilever method, using single boom travelers working on the deck. Falsework bents located at the $\frac{1}{6}$-, $\frac{1}{3}$-, and $\frac{2}{3}$-span panel points were used for the first span and a single bent at the $\frac{2}{3}$ point for each of the remaining four spans. After erection of each of these spans was completed, the offshore end was jacked up sufficiently to release the falsework bent. The top chords, which had temporarily been made continuous with the previous span were then cut, blocking was removed from between the ends of the bottom chords, and the span lowered into its final position on the pier. Erection of the approach spans was substantially completed by December 1, 1950. The travelers were then left in place to dismantle the cable spinning equipment at the anchorages.

Towers

General.—The erection of the main towers was started immediately upon completion of the piers, the first steel for the west tower being set on March 17, 1950, and for the east tower on April 26. Each tower consists of two cellular T-section legs connected at the top (El. +437) and just below the roadway with flat arched portal struts. The tower legs are each battered about 2 ft in their height.

The west tower was fabricated at Ambridge, and the east tower at Gary, Ind. The steel for both towers was shipped to the Wilmington Marine Terminal, thence on barges to the bridge site.

The tower legs were fabricated in thirteen tiers varying in height from 23 ft for the base tier to 40 ft for the tier opposite the lower portal. The height of the tiers below the floor level was increased 8 in. to allow for pier settlement. Generally each tier was divided into three units. The base tier, however, was fabricated in five units and the tier at the lower portal in four units. The heaviest single unit weighed about 54 tons.

Tower Erection.—The bearing areas on the piers had been ground with a carborundum-belt grinding machine to within 0.007-ft variation from a true plane. Just prior to setting the base sections, a thin layer of neat Portland cement was screeded over the bearing area. The steelwork is positively connected to the piers by use of 16 pairs of (6 by 6 by $\frac{3}{4}$ in.) angles for each leg, extending down through sleeves to I-beams embedded in the pier. These angles were spaced to project up into eight of the outside tower cells adjacent to the web plates. Hydraulic jacks resting on the base slabs and pressing up on diaphragm plates inserted between the outstanding legs of the angles were used to induce tensile stresses of 18,000 lb per sq in. in the angles. While maintaining this tension, holes were drilled in the tower webs and the connections riveted. The spaces remaining inside the sleeves were then filled with cement grout.

The first two tiers of both towers were set with a floating derrick which also erected the creeper travelers used to hoist the balance of the tower steelwork. After erecting two tiers, the travelers were, successively, jumped with block and falls and reconnected each time near the top of the tower legs. The

connections were made through 6-in.-diameter pins inserted into steel brackets bolted to the tower sections. As the tower legs are battered, the brackets were provided with adjustable connections to maintain the same relative spacing. Intermediate guide brackets were also installed to keep the travelers upright during the periods of jumping. Temporary cross-struts were placed at El. +307 to stiffen and space the tower legs.

Platforms entirely encircling the tower legs were used for heating the rivets that were projected to the various locations inside the tower legs and portals by pneumatic rivet passers. Cage elevators gave easy access to the roadway level, the temporary cross-struts, and the tower tops, from which points ladders extended up or down to the platforms. The cable saddles were set on brackets on the shore side of the towers in order to place them at the points of balanced free cables. Tower deflections of about 2 ft would otherwise have been required.

The erection of the west tower was completed on August 16, 1950, and the east tower on August 23, 1950. Approximately 4,100 tons of steel were required for each tower.

Cable Spinning

Preparation.—During the latter stages of tower erection, preparations for cable spinning had been started at the anchorages. As has been the practice on the majority of suspension bridges previously constructed, the footbridges were supported on lengths of suspender rope. Four ropes were used for each footbridge that extended from anchorage to tower and tower to tower. These ropes were first laid on the bed of the river and then hoisted to their connections at the towers. The decking for the footbridges consisted of chain link wire fencing stretched across 6-in. by 8-in. timbers spaced about 10 ft center to center and attached to the underside of the ropes. The footbridges were stiffened by the usual arched rope system, making temporary use of the permanent handropes. Cross-bridges were erected at the center and quarter points of the main span. The tramway hauling ropes were carried on steel sheave frames over the saddles and timber bents at about 200-ft intervals along the footbridges. The hauling ropes were driven by two diesel engines, one located at each anchorage. The engines were synchronized by selsyn motor controls to operate in unison with a single control. Electrically controlled clutches were also used, making it possible to stop movement of the hauling ropes from various points throughout the length of the footbridges.

Spinning Procedure.—Actual spinning alternated from one cable to the other, so upon completion of each set of strands, the hauling ropes were interchanged at each drive machine. Twin spinning wheels were used on each part of the ropes so that in full production four loops or eight wires were laid for each trip of the wheels. Leading from the reels, the cable wires were run over the top of a compensating sheave tower with loops inside, in which weighted floating sheaves fluctuated up and down depending upon the relative speeds of the wire reels and the spinning wheels. In their lower positions the floating sheaves actuated brake bands on the reels, thus slowing them or stopping them entirely whenever the spinning wheels stopped.

The cables consist of nineteen strands of 436 wires each, built initially to a hexagonal cross-section with three strands on a side. Approximately 3,360 tons (or 12,725 miles) of wire were required for the two cables. The wire is No. 6 cold-drawn, hot-dipped galvanized in lengths of about 3,000 ft, and spliced with threaded sleeve couplings. The wire was manufactured, spliced, and reeled at Trenton and trucked to the Marine Terminal for transfer to the anchorages by barge.

The cable strands were spun directly in the saddles that were machined to the circular cross-section of the cables. In order to maintain the wires of each strand in their correct relative position, temporary separators and wood blocks were inserted at intervals throughout the lengths of the saddles. For the first layer, these separators consisted of pieces of cable wire inserted in holes drilled in the saddle troughs. The order of spinning was as follows: (*a*) Strands Nos. 1, 2, and 3 forming the bottom layer; (*b*) strands Nos. 4, 5, 6, and 7 occupying the second layer; (*c*) strand No. 10 located at the center of the cable, (*d*) strands Nos. 8, 9, 11, and 12 completing the third layer; (e) strands Nos. 13, 14, 15, and 16 forming the fourth layer; and (*f*) strands Nos. 17, 18, and 19 forming the top layer. When spinning the groups of three strands, only one loop of wire was pulled out each trip from the one anchorage for the middle strand of the group. The center strand (No. 10) was spun by handling it as two strands, and pulling single wire loops from each anchorage with each trip of the wheels. Thus, this strand is formed by four endless lengths of wire instead of two, as for each of the other strands. Upon completion, each strand was compacted and seized at approximately 10-ft intervals with thin metal bands.

Each individual wire was adjusted in each span to hang at the predetermined sag as measured by guide wires initially set by survey instruments. Each completed strand was again adjusted to its correct sag in each span, the first strand being set by instruments and the following in proper relation to the first. Observations for the strand adjustments were made in the early morning or on cloudy days, when all the wire would be more nearly at the same temperature. After the first set, the strand adjustments always consisted of lengthening the strands at the anchorages and slipping them through the saddles to lower them to their correct position in each of the three spans since each set was spun high in each span in order to clear the adjusted strands below. This lengthening was done with a two-part wire rope tackle containing a 60-ton hydraulic pulling jack in one part. This tackle arrangement released the tension in the strand connecting bar, thus permitting the removal of the required number of shims from the adjustable pin connections of these bars to the embedded bars.

Wire spinning started on October 26, 1950, and was completed on January 16, 1951. During this time there was an unusual amount of windy weather, resulting in the loss of 26 working days. The spinning operation was normally on a two-shift basis.

Suspended Spans

Finishing of Cables.—On completion of cable spinning, the equipment at the anchorages was dismantled by the approach travelers. The guy derricks

that had been used in handling the wire reels were re-assembled on the tower portals for erection of the first panels of suspended steelwork and the assembly and disassembly of the suspended span travelers. However, at these locations, steel struts bolted to the tower legs were used in place of guys.

The cables were compacted with the usual device consisting of six hydraulic jacks radially mounted in a steel frame encircling the cable, with each jack actuating a segment of a circular shoe. The compactors were applied at 2-ft to 3-ft intervals, progressing in both directions from the tower tops, and a temporary wire seizing was applied at each point of compaction.

Cable compaction was followed immediately by placement of cable bands and suspenders. The suspenders were all measured while under dead load tension, cut and socketed at Trenton, and trucked to the Marine Terminal for delivery by barge. Overhead trolley lines, formed from the two parts of the hauling ropes, were used to transport the cable bands and shorter suspenders from the tower tops. The long suspenders were hoisted directly from reels mounted on the barges, using a single part hoist rope clipped at intervals to one leg of the suspender rope.

The cable band bolts were tightened with torque wrenches. Extensometer measurements, made on at least two bolts in each band, served as a check on the wrenches. The tightening was repeated as the steel was erected and again just prior to the wrapping of the cables.

The cables were wrapped in the usual manner with No. 8 galvanized annealed wire. This work was done by a machine consisting of a ring that surrounded the cable and was supported on a saddle that slid along the cable. The ring was rotated by an electric motor. Three spools of wrapping wire were mounted on the ring, and the wire unwound as the ring was rotated. The wires were led in tension over and under guides to lie side by side on the cable. As this operation was done prior to the cables reaching full dead load stress, the wire tension was increased considerably above the 300 lb. as specified. At each cable band the wrapping terminates in recesses machined in the ends of the band.

After the wire ends were secured, the recesses were caulked with lead wool. Red lead paste was applied to the cable just prior to wrapping. Three coats of paint then completed the cable work.

Erection of Steel.—The suspended span steelwork, fabricated at Ambridge and Trenton, was all shipped to the Marine Terminal, where a large amount of subassembly and riveting was completed prior to delivery to the bridge site. The floorbeam trusses were completely assembled and riveted and the stiffening trusses were assembled and riveted in double panel units, with the exception of the four center panels of the main span and two end panels of the side spans that had to be erected in individual pieces.

The steelwork erected on the first pass of the travelers, begining at the towers, consisted of the stiffening trusses, floorbeams, top and bottom laterals, inspection walkway, and two lines of stringers. As the profile curvature of the erected steelwork in the earlier stages of this pass was just the reverse of its final curvature, unusual methods were adopted by the contractor to connect the stiffening truss units. Each of the bottom chord splices could have been left

unconnected, which would have made it difficult to develop lateral stiffness to resist movement from wind. Connecting the bottom chords however, in effect, made the forward suspenders too short, so in order to attach them, the stiffening trusses had to be lifted up (or in reality the main cables pulled down) sufficiently to slip the suspender sockets under their seat angle connections. This was done with blocks and falls, the upper block being connected to a shorter pair of suspenders, temporarily placed over the main cable for this purpose, and the lower block connected to the top of bottom chord of the stiffening truss. The reverse curvature, however, was too great to permit this treatment for every stage, so at two points in each side of the main span and at one point in the side spans, the bottom chords and laterals were temporarily left unconnected. Wire ropes were used at these points to maintain continuity of the lateral system.

The truss members in the four center panels of the main span and the two end panels of the side spans were erected individually. The closure of the stiffening trusses offered no difficulty as, being discontinuous at the towers, their relative positions were easily adjusted to match the closing members. Erection started on February 16, 1951, and closure of the center span was accomplished on April 22, 1951, with the side spans being completed during the following week. The travelers then retraced their way back to the towers, setting the remainder of the steelwork. As the dead load was added, the tower tops were jacked shoreward under the cable saddles in four increments to their normal positions, after which holes were drilled and the permanent bolts placed. About 7,800 tons of steel were required for the suspended spans.

Roadway Paving

The two roadways, each 24 ft wide, were constructed of reinforced concrete with the riding surfaces pitched to the side and center curbs. The formwork was extremely simple. Cross-timbers resting on the bottom flanges of the stringers supported longitudinal timbers adjacent to the stringers. These in turn carried an upper set of cross-timbers framed at either end to the bevel of the haunches adjacent to the stringers. These timbers were forced up against the underside of the stringer flanges, wooden wedges being used to adjust them to the correct plane. Plywood decking completed the formwork. Only a nominal amount of nailing of the plywood was required to hold it in contact with the cross-timbers which in turn were toe-nailed to the longitudinal timbers below. Joints in the plywood were sealed with adhesive tape. Thus, the erection and stripping of the forms were done with a minimum of damage, permitting several reuses of the form material. Stripping of the approach roadway forms was done from traveling platforms under the deck steelwork, supported by two lines of hangers and inverted I-beam trolleys that engaged longitudinal beams attached to the top surface of the platforms. The hangers and trolleys were progressively shifted ahead as the platform moved forward. Scaffolding supported on wire ropes was used for stripping the forms for the suspended spans.

The roadways were poured full width and finished with standard highway screed machines. These units ran on rails formed by 4-in. H-beams bolted

with flanges vertical to the tops of the curbs, thus bridging the numerous rivet heads at these locations.

The concrete was mixed at central mixing plants and trucked to the bridge deck. Here it was discharged into motor buggies that operated on timber runways placed over the walkways and outer edge of the roadways. Pouring always began at the far end of each panel and progressed toward the point of supply. As the dumping platform moved ahead, the sections of the runway overhanging the curb had to be removed to clear the screed machine. Only a small amount of longitudinal screeding and floating by hand following the machine-finishing was required to produce a satisfactory surface. Brooming and spraying with curing compound completed the paving operation.

The placement of the concrete on the suspended spans was carefully scheduled to introduce the load as uniformly as possible and prevent excessive distortions of the steelwork. This was done in four passes, progressing in each case, from east to west. The roadway slabs on the suspended spans are divided into panels by transverse stress joints spaced about 104 ft apart. For each pass, generally every fourth panel was poured. In the two roadways these also were staggered by one panel, so that the forms could be quickly shifted laterally from one roadway to the other with no cutting The first pass started about 200 ft west of the east tower, and the second pass at the east anchorage. The forms were left in place for 7 days in lieu of curing the underside of the slab. To speed up the operation, sufficient material was made available to form one complete roadway from anchorage to anchorage. All concrete for the suspended span and anchorage roadways was delivered to the west anchorage.

Completion of Anchorage

During the period of erecting the suspended steelwork and placing the concrete deck, the balance of the anchorage concrete was poured. This work had to be coordinated with the addition of the dead load to the cables so as to avoid excessive soil pressures at the rear of the anchorage piers. Approximately 7,250 cu yd of concrete were required to complete each anchorage. On the Delaware side, this concrete also was mixed at a central mixing plant, and delivered by truck to the site at deck level, at which point it was distributed by conventional methods, including pumping. On the New Jersey side the operation was essentially similar. Here, however, the concrete was largely mixed at the site, with dry batches delivered by truck.

Conclusion

The bridge was opened for traffic on August 16, 1951, about 2 yr and 6 mo from the beginning of construction in February, 1949. However, considerable work remains to be done. This work consists principally of the remainder of the painting, the installation of the electrical system, and the construction of the tower pier fenders. The fenders will be cantilevered from the piers, connecting to steel struts that were inbedded in the concrete. (The contracts awarded in the course of bridge construction and the contractors are listed in Table 1, with approximate costs.)

Table 1.—Contracts Awarded for Construction of the Delaware Memorial Bridge (Below Wilmington, Del.)

Contract No.	Description	Contractor	Estimated Cost
1	Borings	Sprague and Henwood, Inc.	$ 33,206
2	Tower piers and anchorage foundations	Merritt-Chapman & Scott Corp., New York, N. Y.	11,615,407
3A	Approach river piers	Merritt-Chapman & Scott Corp., New York, N. Y.	1,223,797
3B	West approach land piers	Conduit and Foundation Corp., Philadelphia, Pa.	582,106
3C	East approach land piers	Lewis and Bowman, Inc., Goldsboro, N. C.	861,558
3D	Anchorage blocks	Merritt-Chapman & Scott Corp., New York, N. Y.	1,856,946
4	Towers and suspended steelwork	American Bridge Co., Philadelphia, Pa.	6,106,000
5	Cables and suspenders	American Bridge Co., Philadelphia, Pa.	2,311,985
6	Approach superstructure steelwork	American Bridge Co., Philadelphia, Pa.	5,383,294
7A	Anchorage tops	Lewis and Bowman, Inc., Goldsboro, N. C.	1,132,550
7B	Concrete deck	The Whiting-Turner Contracting Co., Baltimore, Md.	1,043,329
8	Field painting	Buffalo Sheeting & Painting Co., Buffalo, N. Y.	338,324
9	Fenders	Merritt-Chapman & Scott Corp., New York, N. Y.	298,880
10	Electrical installation	Garrett Miller & Co., Wilmington, Del.	249,133
11	Tower elevators	Otis Elevator Co., Philadelphia, Pa.	32,985
12	East approach grading	Henry C. Eastburn & Son, Newark, Del.	55,126
13	East approach paving	Newark Construction Co., Newark, Del.	243,368
14	West approach grading	Henry C. Eastburn & Son, Newark, Del.	148,294
15	West approach paving	James Julian, Elsmere, Del.	322,602
16	Pennsylvania Railroad Overpass	Conduit and Foundation Corp., Philadelphia, Pa.	194,455
17	Front range light structure	Thomas Earle and Sons, Inc., Philadelphia, Pa.	57,004
18	New Castle Interchange ramps	....	211,400
19	Administration Bldg. and toll booths, etc.	Cantera Construction Co., Wilmingron, Del.	366,197
20	Maintenance Bldg. and additional toll facilities	....	107,000
21	West approach embankment	Citro and Sons, Inc., Wilmington, Del.	21,965
22	Planting operations	David Bachtle, Mendenhall, Pa.	26,408

Acknowledgment

The firm of Howard, Needles, Tammen & Bergendoff are the engineers, and O. H. Ammann, M. ASCE, and the firm of Moran, Proctor, Freeman and Mueser, are the consultants. A. Gordon Lorimer is the consulting architect, and the writer is the project engineer.

The director of the project, representing the State of Delaware is W. A. McWilliams, M. ASCE, former chief engineer of the State Highway Department. He was preceded by W. W. Mack, who had also served as chief engineer of the department and by Gen. Eugene Reybold, M. ASCE, retired chief of the Engineer Corps.